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WORKSHOP ON LIGHT SCATTERING AND RELATED PHENOMENA

ARCACHON, FRANCE

15-19 MAY 1995

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Organisé par le CEA/CESTA
avec l'aide de l'Ecole Centrale de Paris

Michel JOSSE
CESTA/DT/PE/IRM

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INTRODUCTION

Ces journées de travail sur la diffusion de la lumière par les surfaces rugueuses sont organisées par le CEA/CESTA au Palatium à Arcachon.

Les conférences auront lieu pendant quatre jours, du lundi 15 mai au jeudi 18 mai 1995.

Le vendredi 19 mai (matin) sera consacré à la visite de certaines installations du CESTA.

Nous comptons réunir environ 35 personnes pour ces journées de travail.

La liste des participants et intervenants est donnée en page 4.

Dans la mesure du possible, nous avons essayé de conserver un thème unique pour chaque demi-journée.

Le nombre de participants a été volontairement restreint pour que les exposés puissent être suivis d'un débat animé et constructif.

L'organisation de ces conférences est présentée en page 5.

Les pages suivantes présentent les abstracts des intervenants classés par ordre alphabétique.

Nous tenons à remercier l'Ecole Centrale de Paris pour l'aide financière qu'elle a apportée à l'organisation de ces journées de travail.

Egalement nous remercions ISIS (Institute for Surface and Interface Science), Université de Californie à Irvine pour son aide aux frais de déplacement des personnels du Gouvernement Américain pour participer aux journées de travail.

Nous remercions l'US Army Research Office pour leur aide financière.

Organisateur : Michel JOSSE
CEA/CESTA/DT/PE/IRM

INTRODUCTION

This Workshop on light scattering and related phenomena is organized by CEA/CESTA at the Palatium in Arcachon.

The presentations will take place during four days, from Monday May 15 to Thursday May 18 1995.

On Friday morning May 19, there will be a visit of some of the CESTA facilities.

A list of the participants and the speakers is presented on page 4.

As far as possible, we have tried to dedicate a common subject to each half-day session.

The number of participants has been expressly limited, in order to favor discussion time.

The organization of the workshop is presented on page 5. On the following pages are presented the abstracts of the speakers (in alphabetical order).

We would like to thank Ecole Centrale de Paris for their financial support.

We thank ISIS (Institute for Surface and Interface Science), for their financial support in providing travel for american government employees.

We also thank the U.S. Army Research Office for their financial support.

PARTICIPANTS

NAMES	SPEAKER	ABSTRACTS
Usman AHMED	May be 2 days	NO
Claude AMRA	YES	YES
Michael ARNOLD	YES	YES
Christophe BAYLARD	NO	NO
Jean BENNETT	YES	YES
Mans BJUGGREN	YES	YES
Gary BROWN	YES	YES
Bernard CAPBERN	NO	NO
Bernard COUSIN	YES	YES
Sheshao FENG, Kirll SHTENGEL	YES	YES
Walter A. FLOOD	NO	NO
V. FREILICHER	YES	YES
Iosif FUKS	YES	YES
Jean Jacques GREFFET	YES	YES
Jean Jacques GREFFET, F. PINCEMIN	YES	YES
Zuhan GU	YES	YES
Akira ISHIMARU	YES	YES
Michel JOSSE	YES	YES
Joseph KUPERSZTYCH	NO	NO
Janig LE GALL	YES	YES
Gérard LEFLOUR	NO	NO
Tamara LESKOVA	YES	YES
Arthur McGURN	YES	YES
Alex MARADUDIN	YES	YES
Eugenio MENDEZ	YES	YES
Thierry MICHEL	YES	YES
Manuel NIETO-VESPERINAS	YES	YES
Jean Jacques NIEZ	YES	YES
Kevin O'DONNELL	YES	YES
M. PEYRARD	NO	YES
Marc SAILLARD	YES	YES
José SANCHEZ-GIL	YES	YES
Anne SENTENAC	YES	YES
Valerian TATARSKII	YES	YES
Eric THORSOS	YES	YES
A. TIMTCHENKO	YES	YES
Phuc TRAN	YES	YES
Leung TSANG	YES	YES
Françoise VARNIER	NO	NO
Nicolas VUKADINOVIC	NO	NO

SCHEDULE

Monday	Tuesday	Wednesday	Thursday
Morning			
J. Bennett	G. Brown	M. Bjuggren	
A.Maradudin	Freilicher	B. Cousin	T. Leskova
		C. Amra	T. Leskova
	A. Ishimaru	M. Josse	E. Mendez
Afternoon			
	I. Fuks	T. Michel	M. Saillard
A. McGurn	Z. Gu	J. Sanchez-Gil	V. Tatarski
K. O'Donnell	A. Timtchenko	M. Nieto-Vesperinas	E. Thorsos
M. Arnold		J. Legall	

C. AMRA, C. DEUMIE, S. MAURE, R. RANIER, G. ALBRAND, H. GIOVANNINI
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LIGHT SCATTERING AS A PROBE FOR INTERFACES AND BULKS IN LOW-LOSS OPTICAL THIN FILM MULTILAYERS

Optical filters and multilayer waveguides are today required to present minimal losses (close to 10^{-6} in free space) for many applications such as high power laser and optical telecommunications, integrated optics... In our laboratory these multilayer components are produced under vacuum with different techniques such as Reactive Evaporation, Ion Assisted Deposition and Ion Plating. In most cases the thin film layers consist of oxyde materials for visible, infrared and UV regions such as TiO_2, Ta_2O_5, HfO_2, SiO_2...

The requirement of minimal losses concerns both absorption and scattering from the multilayers. Absorption is usually measured via photothermal techniques that allow to detect levels lower than 10^{-6}. In the same way, scattering must be measured with high accuracy, since high polished substrates (with 0.1 nm roughness) scatter some 10^{-7} of the incident flux in whole space.

In this paper, we present a brief overview of our work concerning light scattering in thin film multilayers. In a general way, we develop experimental and theoretical tools that allow us to characterize the microstructure of thin film multilayers from the knowledge of their angular scattering curves :

- The first problem to deal with concerns the origin of light scattering (surface roughnesses or bulk inhomogeneities) in the optical components. From electromagnetic theories we show that the angular or spectral polarization ratio of the scattered light consitutes an adequate tool to separate surface and bulk effects. In addition, ellipsometric measuments of light scattering are performed at each direction and provide us a phase term variations that increases the accuracy and confirms our conclusions.

- An immediate application is the characterization of optical polished substrates that present roughnesses in the range 0.1 nm to 5 nm. The light scattering technique provides bidimensional roughness sepctrum, autocorrelation functions and spectral isotropy curves of the surface defects. Measurements are performed with wavelengths extending from the near UV (325 nm) to the mid-infrared regions (10.6 μm), which allows to measure the roughness spectra in a large macroscopic (optical) bandwidth. In addition, extrapolation at high spatial frequencies is reached with Atomic Force Microscopy and the results demonstrate large agreement (from the macroscopic to the microscopic) between the two techniques. As a conclusion for these bare substrates, we study the variation of roughness with wavelength or frequency bandwidth, which leads us to discuss the opportunity of multiscale roughness or polishing.

- Another point to deal with concerns the modification of roughness resulting from the deposition of the multilayers. This information is taken in account via cross-correlation coefficients involved in the theoretical models, that describe the mutual coherence of scattering sources at each interface of the stack. For high-quality optics produced by IAD and Ion Plating, light scattering allows us to show that the substrate roughness constitutes the lower threshold of scattering, since it is replicated at each interface of the multilayers. Atomic Force measurements are also performed on the samples and prove that the conclusions are multiscale.

- At last we must take into account the presence of a few localized defects (diameter close to 0.1 μm) that may create a predominant scattering at levels lower than 10^{-5}. In this situation, surface and bulk effects must be discussed together, including random and deterministic aspects.

- In the same way light scattering is responsible for loss anomalies in the attenuation process of a guided mode inside a multilayer planar structure. This point is discussed with the help of photothermal deflection measurements and theoretical models that predict the influence of roughness and inhomogeneities in multilayer waveguides.

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ENHANCED BACKSCATTERING OF LIGHT FROM WEAKLY ROUGH METALLIC SURFACES

The possible effect of enhanced backscattering of light form weakly rough metallic surfaces is related to multiple scattering processes involving Surface-Plasmon-Polaritons (SPPs). The relevant two-dimensional scattering theory was developed by BROWN et al [1] and McGURN and MARADUDIN [2]. We use this theory for the calculation of the backscattering peak height above the diffuse background intensity. We vary the wavelength λ of the incident light and the correlation length τ and root mean square roughness σ of a silver surface in order to optimize these parameters for the experimental confirmation of enhanced backscattering. Furthermore we discuss the different dampings (absorption Δ_{ε}, SPP directional scattering Δ_{sp}, and reradiation Δ_{rad}) of a SPP propagating along a rough surface and include the radiation damping Δ_{rad} into the calculation of the effect.

[1] G. Brown, V. Celli, M. Haller, A.A. Maradudin and A. Marvin, Phys. Rev. B31, 4993 (1985)

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CHARACTERIZATION OF OPTICAL SURFACES

Scattered light is a very important problem in high quality optical systems. Scattering redirects light from where it is designed to go into undesirable directions. For example, scattering can produce a haze on photographs and on images of point sources such as stars, and scattering from laser mirrors can prevent a laser from lasing. Most scattering arises from imperfections on optical surfaces or in the coatings on the surfaces. Techniques available for surface characterization include microscopes to provide pictures of surfaces, optical and mechanical profilers to produce surface profiles with quantitative height information, and scatterometers to measure surface scattering. Theories are necessary to correlate scattering with surface roughness, power spectral density, and other surface statistics. Recently, the atomic force microscope has been used to show surface detail on a much finer lateral scale than is possible with other techniques. Surfaces whose roughness heights are large compared to the wavelength of light pose special problems. However, some possible characterization techniques will be suggested. Cleaning of optical surfaces is an important part of surface caracterization since the surfaces to be measured should be free of dirt either in the form of particulates or films. In summary, surface characterization is necessary to understand what is on a surface in order to reduce scattering and to provide better input to theoretical models of rough surfaces.

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CHARACTERIZATION OF ENGINEERING SURFACES BY TOTAL INTEGRATED INFRARED SCATTERING

As high quality engineering surfaces are gaining in importance in industry, so are the surface quality requirements. These surfaces have rms roughness typically ranging from some nanometers up to several micrometers. Althrough several techniques exist for rough surface characterization, from traditional stylus profilometers to modern three-dimensional measurement instruments, there is a need for a fast, area-covering technique. An efficient method for the characterization of smooth surfaces is elastic light scattering. At visible wavelengths the limits on roughness range and spatial frequency range make the method unsuitable for characterizing engineering surfaces. We have used total integrated scattering at 10.6 μm wavelength to measure rms roughness up to a couple of micrometers. The instrument design and properties are reviewed. We present results from measurements on metal surfaces of various processing. Good correspondance with mechanical stylus measurements exists for surfaces with rms roughness in the range from 0.05 μm to 1.7 μm. The technique shows potential for quality inspection of engineering surfaces.

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A NEW NUMERICAL SCATTERING METHOD

Most analytical approximations for dealing with scattering from rough surfaces achieve their success over a fairly restrictive range of surfaces parameters, but there are usually well understood reasons behind these limitations. Examples of these are the Kirchhoff approximation, the small perturbation method, and the method of smoothing ; the first two comprise what might be called single scale approximations while the third is capable of dealing with multiple scales of roughness. In the domain of numerical scatterring, it may not always be possible to tie a certain method to a range of validity. In fact, there may be cases where the approximation may produce surface fields which are in error but lead to a scattered field which is totally acceptable in its accuracy. This is one of the properties of a numerical approximation to be presented here.

For the case of scattering of an incident field by a perfect electrically conducting roughened planar surface, the current induced on the surface is given by the Magnetic Field Integral Equation. For one dimensional roughness, the surface integral becomes a one dimensional integral which can be split into two parts ; one having limits (-inf, x) and the second having limits (x, inf). Using this partitioning of the interaction integral on the surface, it is possible to derive a new integral equation of the second kind that has a new Born term and a new propagator. The Born term involves inverses of the partitioned integral operators but can be easily solved when the integrals are discretized. In fact, the inverses can be computed without the need to invert a matrix and this reduces both the execution time and the storage requirements. If the current is sampled at N points along the surface, a conventional method of moments solutions involves roughly N^3 multiplications while this approach needs N^2. Further, there is no need to store the full propagator matrix as only parts of it are ever used. It can also be shown that if one goes beyond the Born term and calculates higher iterates, the resulting series converges very rapidly.

We should point out that a slightly different integral formalism was first developed by Dennis Holliday and his group at RDA Logicon but their result is essentially the same as ours. The remainder of our paper will be devoted to illustrating the robustness of the new Born term in so far as the scattered field is concerned. Holliday, et. al. rejected the Born term because they found that it produced errors in the surface fields or currents. However, it will be shown that these errors are relatively small and, even more importantly, they have a very small spatial support on the surface and hence lead to nearly omnidirectional scattering thereby further diminishing their effect on the scatted field. Results particular to enhancement will be presented.

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RECENT RESULTS IN THE ANALYSIS OF NEAR FIELD IMAGES

Several techniques have demonstrated the possibility of producing images with a subwavelength resolution by using the near field. In this work, we analyse the process of image formation.

The more general problem requires to account for the multiple scattering between the tip and the object under inspection. One of the techniques consists in detecting the near field with a very thin optical fiber placed at 50 nm of the surface. We have developped a numerial simulation in order to investigate if the tip can be reasonably considered as being a passive probe of the near field. We will show that it is possible to define a transfer function between the detected signal and the square modulus of the near field for a 2D problem in s-polarization.

A key issue is to establish the relationship between the structrure of the object and the detected signal. To this end, we have developed a perturbative analysis of the near field and we have investigated its range of validity in the near field. This approach allows to derive two simple results. First, we have shown that the relevant parameter is the product of the dielectric contrast by the surface profile. In other words, a submerged waveguide might produce exactly the same field that a bump on the surface provided that the integral of the dielectric contrast along a vertical is the same. The second simple result is that the intensity behaves essentially as a hologram of the surface profile. This means that both the phase and the amplitude of the Fourier spectrum of the (equivalent) surface profile is encoded in the signal detected.

As a consequence one may design an inversion procedure that allows to retrieve the surface profile from the data. Results of inversion of simulated data will be presented. It will be shown that the resolution is enhanced by the reconstruction procedure.

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ANGULAR MEASUREMENTS OF LIGHT SCATTERING AT UV, VISIBLE AND INFRARED WAVELENGTHS : DESCRIPTION OF TWO SCATTEROMETERS

Light scattering from optical surfaces often constitutes a key point for many applications such as optical telecommunications[1], space imaging and low-loss thin film multilayers for high power lasers... Therefore it is very necessary to develop apparatuses that allow to measure, at each direction of space and for several wavelengths, scattering levels resulting from surface roughness or bulk inhomogeneities in the optical components[2,3]. The dynamic range of the measurements must be very wide because the angular scattered intensity approximately varies from $1/\pi$ (case of a NO-absorbing lambertian diffuser) to some 10^{-7} of the incident power (case of a high-polished substrate, with 0.1 nm roughness).

In this paper we present two multi-wavelength angle-resolved scatterometers that were developed at CNES and at LOSCM[4]. Special care is taken with the quality of the measurements, that is, calibration, linearity, parasitic light and dynamic range. The wavelengths of measurements extend from 325 nm to 10.6 µm.

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SCATTERING FROM BOUNDED MEDIA WITH ROUGH SURFACES

The paper presents the theory of scattering from dielectric and metallic layers with randomly rough boundaries. Angular distribution of intensity is studied for waves scattered by and transmitted through slightly rough interface of systems that support discrete spectrum - surface waves or waveguide modes. It is shown analytically that along with the enhancement in the retroreflected direction there exist satellite enhanced peaks of reflected and transmitted intensity at angles that are defined by degenerated time-reversal symmetry. The coherent enhancement appears as the result of competition of two mechanisms : multiple scattering of modes along the interface and leakage of energy to the upper halfspace. By computer simulation we study the scattering of electromagnetic waves of different polarizations from a randomly rough dielectric film deposited on a planar perfectly conducting surface, and the transmission through a free-standing metallic film. The numerical results are in a good agreement with the theoretical predictions.

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SURFACE ROUGHNESS AND UNDERGROUND REMOTE SENSING

Backscatter from an object buried under a layer of soil with the rough surface is studied theoretically. Despite the radar signal from an "ideal" subsurface body itself is negligibly small the scatter from a roughness of air-soil boundary provides (due to interference between the specular reflection from the object) the backscatter signal that depends on location of the object and therefore may be used for its detection. The contrast coefficients are introduced as a quantitative characteristics of the relative contribution of the strong subsurface specular reflector into the signal baskscattered against the background of scattering by the air-soil interface. Contrast coefficients are calculated and the maximal depth of detection of subsurface plane objects is estimated for different types of soils (sand, clay) and for different polarizations and frequencies of the probe signal. The value of this coefficient is an oscillation function of the wavelength, angle of incidence and the depth of the object. It is shown that in a wide range of incident angles the mean value (averaged over the oscillations) of the contrast coefficient for the horizontal polarization (vector of the electrical field is perpendicular to the plane of incidence) is much larger than that one for vertical polarization. It increases as the angle of incidence for horizontal polarization increases and decreases (up to the Brewster angle) for vertical polarization. In the first order of the perturbation theory method for the wave scatter by the rough surface the contrast coefficient for the vertical polarization is zero when the angle of incidence equals to the Brewster angle. For the subsurface plane interfaces between homogeneous layers that are paralleled to the mean air-soil surface the value of contrast is independent of the surface parameters-heights, lenghts and even spatial power spectrum of roughness. In the particular case of the perfectly conducting plane object submerged in the NOabsorbable medium the contrast coefficient for the horizontal polarization may reach the value as high as 25 due single reflection only.

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PROPAGATION OF A SURFACE PLASMON POLARITON ALONG A RANDOM GRATING PERIODIC ON AVERAGE

When a surface plasmon polariton (SPP) is launched on a surface supporting a finite grating, it may be reflected if the frequency lies in the gap. Such a system behaves like a photonic band structure (PBS) material. We have developed a numerical simulation that allows to study the influence of a defect in the grating. We will show that a peak of transmittivity of the finite grating appears for a frequency that lies in the gap. The study of the near field shows that this peak corresponds to the excitation of a localized mode. The behavior of the near field supports the physical model of hopping transmission.

The second part of our study deals with the propagation of the SPP on a random grating periodic on average. We will analyse the effects on the gap and we will discuss the behavior of the localization length near the gap. The existence of Anderson localization will be discussed.

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OBSERVATION OF GIANT ENHANCED BACKSCATTERING OF LIGHT FROM WEAKLY ROUGH DIELECTRIC FILMS ON REFLECTING METAL SUBSTRATES

The enhanced backscattering of light from a randomly rough surface, which is manifested as a narrow peak in the retroreflection direction in the angular distribution of the intensity of the light that is scattered diffusely, has been extensively investigated. Both theoretical and experimental investigations have shown that the height of the peak is never more than twice the height of the background at the position of the peak. In this paper, we report the observation of a giant enhanced backscattering of light from a randomly rough dielectric film on a reflecting metal substrate, in which the ratio of the height of the peak to the height of the background at its position is greater than 10. It is found that this giant enhanced backscattering peak is accompanied by concentric circular interference fringes, whose axis is normal to the mean scattering surface, with both the specular and baskscattering peak on the same ring. A possible mechanism for the giant enhanced backscattering is suggested.

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POLARIMETRIC SCATTERING THEORY FOR HIGH-SLOPE ROUGH SURFACES

Electromagnetic scattering by rough surfaces is important in several disciplines including geophysical remote sensing, ocean acoustics, surface optics, and ultrasound imaging of biological media. For surfaces with small rms height, the conventional perturbation theory is applicable while for surfaces with large radii of curvature, the Kirchhoff theory gives good solutions. In recent years, several improved theories have been proposed to extend the range of validity of surface parameters, and numerical simulation studies have been reported. We present a theory based on the first- and second-order Kirchhoff approximations with angular and propagation shadowing. Its range of validity is considerably larger than most of the previous theories using Krichhoff approximations, and it is applicable to rough surfaces with high slopes of order unity. There are two important points in the theory. The first is that the Green's function is expressed by the Fourier transform is the y-z plane transverse to the propagation distance x, rather than usual Fourier transform in the x-y plane parallel to the average rough surface. The second important point is that for second-order scattering, we make use of angular and propagation shadowing functions. These two features make possible the expansion of the range of validity of the theory beyond those for conventional techniques.

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VISIBLE AND INFRARED CHARACTERIZATION OF TEST SAMPLES AT CESTA

At CESTA, during the last few years we have been concerned with the effects of visible and infrared light on rough surfaces. For that purpose some experimental set-ups have been developed to messure the optical properties of materials on test samples.

We shall present the equipment that we have implemented at CESTA, that perform: bidirectional reflectivity, directional reflectivity and bidirectional transmittivity at 0.633, 5.4 and 10.6 μm, spectral directional emissivity at high temperature (between 80 and 600°C) and at low temperature (between -60 and 80°C), absorptivity using the mirage effect in the visible and at 10 μm, infrared spectra between 2 and 20 μm using a Fourier Transform spectrometer, optical indices between 2 and 20 μm using an ellipsometer, thin films measurements, 1-D and 2-D profile measurements using an optical profilometer, and a scanning beam electronic microscope.

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PHOTOTHERMAL BEAM DEFLECTION APPLIED TO THE STUDY OF SURFACE PLASMON-POLARITONS ON ROUGH METAL SURFACES

A photothermal beam deflection (PTD) experiment with a variable pump angle is presented. This set-up is used to study surface plasmons excitation at 10.6 μm in gold-coated gratings. The gratings which were made by reactive ion etching of silicon present a rectangular profile geometry. A conventional 1-D grating and a 2-D bigrating are studied. In the case of the bigrating the two perpendicularly crossing corrugations are indentical. Both gratings exhibit the same amplitude (h = 0.8 μm) and the same period (10 μm).

As the incidence angle of the pump varies, the photothermal beam deflection signal exhibits well defined peaks which correspond to the surface plasmon excitation. For the 1-D grating, the measured absorptivity is compared to a numerical simulation based on a volume integral method. A good agreement is obtained between experiment and calculation. The photothermal measurements on the bigrating were performed for different values of the azimuthal angle, i.e. the angle betwwen the plane of incidence and the axis of the grating. In this NO-coplanar geometry, the angular positions of the absorption of the peaks are compared with the values deduced from the dispersion relation for unpertubated surface plasmons.

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SECOND HARMONIC GENERATION BY SURFACE POLARITONS AT A SLIGHTLY ROUGH METAL FILM

A general diffuse scattering and a localization peak of second harmonic of light generated by surface polaritons on a rough metal surface in the directions around the normal to the mean surface is studied. It is shown that the presence of roughness on the surface breaks the symmetry of the NOlinear interaction of counterpropapating p-polarized waves and, as a consequence, leads to the appearance of both the diffuse background and to the peak in the angular distribution of the intensity of second harmonic radiation. The localization peak in the direction normal to the mean surface is shown to split into two components.

The experimental observation of the localization peak in the angular distribution of the intensity of second harmonic light radiated in the direction normal to the mean surface of a slightly rough silver film is presented.

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ROUGHNESS INDUCED ABSORPTION IN LAYERED SUPERCONDUCTORS

The effect of weak surface roughness on the reflectivity of highly anisotropic layered metals is studied. We have shown that the strong optical anisotropy leads to the enhancement of the processes of surface polarition excitation via surface roughness. The results are applied to the reflectivity spectra of c-axis oriented layered superconductors.

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THE SURFACE PLASMON POLARITON MECHANISM FOR THE ENHANCED BACKSCATTERING OF LIGHT FROM RANDOMLY ROUGH METAL SURFACES

Perturbation theory results are presented for the reflection of light from one-dimensional random rough surfaces, one-dimensional random rough surfaces which are periodic on average and two-dimensional random rough surfaces. Particular attention is given to weakly rough surfaces with roughness power spectra which are NO-zero only in a narrow range of wavenumbers about the wavenumber of the surface plasmon polariton supported by the surface at the frequency of the incident light. The enhanced backscattering from such surfaces is shown to arise from phase coherent interference of counter-propagating surface plasmon polaritons. West and O'Donnell (J. Opt. Soc. Am A, (1995)) first proposed and experimentally studied the scattering and enhanced backscattering from such surfaces with power spectra NO-zero only in the neighborhood of the surface plasmon polariton wavenumbers for one-dimensional random rough gold surfaces. Excellent agreement is found between these experiments ands our one-dimensional perturbation theory results, confirming the surface plasmon polariton mechanism for enhanced backscattering. Theoretical results are also presented at optical wavelengths for one-dimensional periodic on average and two-dimensional randomly rough gold and silver surfaces which have roughness power spectra of the types mentioned above.

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NUMERICAL SIMULATION STUDIES OF THE SCATTERING OF ELECTROMAGNETIC WAVES FROM TWO-DIMENSIONAL RANDOMLY ROUGH METAL SURFACES

We present results of numerical simulation calculations of the in-plane and out-of-plane, co- and cross-polarized scattering of p-polarized electromagnetic waves incident normally on a two-dimensional, randomly rough metal surface, obtained by three approaches. In the first a system of six coupled inhomogeneous integral equations for the four independent components of the surface electric and magnetic current densities and the surface electric and magnetic charge densities, derived from the Stratton-Chu equations, is converted into a system of matrix equations that is solved by Neumann-Liouville iteration. The scattered electric and magnetic fields are obtained from the solution. In the second approach the system of six integral equations is reduced to a system of four integral equations by means of the replacement of the surface charge densities by surface divergences of the surface current densities. In the third approach this system of four integral equations for the independent components of the surface currents is reduced to a system of two coupled equations by the use of an impedance boundary condition for a two-dimensional rough metal surface. Each of these approaches is used to study the scattering of electromagnetic waves from a large rms height, large rms slope, two-dimensional randomly rough metal surface characterized by a Gaussian power spectrum $g(|\vec{k}_{//}|) = \pi a^2 \exp(-k_{//}a^2/4)$, where $\vec{k}_{//} = (k_1, k_2, 0)$ is two-dimensional wave vector in the plane of the mean scattering surface. The results obtained are in good agreement with each other. Enhanced backscattering is predicted. The first of these approaches has also been applied to the scattering of electromagnetic waves form two dimensional random metal surface characterized by the power spectrum $g(|\vec{k}_{//}|) = 4\pi\theta(|\vec{k}_{//}| - k_1)\theta(k_2 - |\vec{k}_{//}|)/(k_2^2 - k_1^2)\ (k_2 > k_1)$, where $\theta(x)$ is the Heaviside unit step function, and $k_{sp}(\omega)$ is the wave number of the surface plasmon polariton supported by the planar metal-vacuum interface at the frequency ω of the incident electromagnetic wave. The difference $k_2 - k_1 = 2(\omega/c)\sin\theta_{max}$ defines the limits on the polar angles of incidence and scattering, $-\theta_{max} < \theta_{0,s} < \theta_{max}$, within which the incident electromagnetic field can couple into surface plasmon polaritons through the surface roughness, and the surface plasmon polaritons can couple to scattered volume waves propagating away from the surface. The preferential excitation of surface plasmon polaritons by the incident electromagnetic field sharpens the enhanced backscattering peak relative to its form when a Gaussian power spectrum is used.

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RECENT STUDIES ON THE SCATTERING OF LIGHT BY ONE-DIMENSIONAL SURFACES

In this talk, we will present the results of some recent studies on the scattering of light by one-dimensional (1D) surfaces.

First, a study of the statistics of the polarization properies of 1-D randomly rough surfaces will be presented. Based on the assumption that the s an p components of the electric field vector constitute correlated circular complex Gaussian processes, some first order statistical properties of the polarization of scattered fields can be established. In particular, results for the Probability Density Function (PDF) of the Stokes parameters and their correlations will be given. For each realization of a random surface, the random Mueller matrix elements associated with the sample may be determined from measurements of the Stokes parameters of the scattered light. Choosing a + 45° linear polarization for the incident field, we are then able to study the statistics of the Mueller matrix elements. Numerical and experimental data on the statistics of the Muluer matrix elements will be presented and compared with theoretical results. Some examples that illustrate the usefulness and significance of our results will be presented.

Recently, numerical techniques based on an integral "equation approach" have been widely used to solve light scattering problems with 1-D surfaces. In the usual formulation of the method it is assumed that the surface profile can be represented by a single-valued function. In the second part of the presentation, we will describe a technique that extends the applicability of this approach to surfaces whose profile is multi-valued. First, a systematic way of finding a parametric description of a given profile is proposed. This enables us to work with rather arbitrary surfaces, including reentrant ones. Using this formalism, we also derive an impedance boundary condition for the field on the surface. Some numerical results will be presented and comparisons with other methods will be made. Finally, we present results of the application of this techique to the scattering of light by a Koch fractal.

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RESONANT LIGHT SCATTERING FROM RANDOMLY ROUGH METAL SURFACES

We present calculations of the intensity of the light diffusely scattered from a randomly rough metal surface. In the regime of interest a significant component of the scattering may be attributed to the excitation of surface polaritons by the incident beam. The conditions under which the angular distribution of the diffuse intensities may exhibit an enhanced backscattering peak are investigated. When the random roughness is superimposed on a periodic grating, the properties of the diffusely scattered light are strongly influenced by the grating. A backscattering enhancement may be observed at wavelengths longer than twice the period of the grating. At wavelengths comparable to twice that period, the grating suppresses resonant scattering. At shorter wavelengths, where a grating anomaly is found, the diffuse scattering displays diffuse bands or minima at the angle of the anomaly, depending on the angle of incidence. Furthermore an enhancement of these diffuse light bands is observed when they coincide with the retroreflection direction. Other manifestations of the resonant excitation of surface polaritons are predicted in the case of an incident beam whose width is comparable to the mean free path of the resonant mode or, under pulse illumination, when the decay constant of the mode is comparable to the duration of the incident pulse.

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LIGHT SCATTERING FROM OBJECTS IN FRONT OF ROUGH SURFACES : ITS RELEVANCE TO NEAR FIELD OPTICS

We shall give an overview of the study of the scattering of light and other electromagnetic waves from systems formed by a rough interface with an object in front of it. This problem is of present interest in the analysis of the interaction of fields scattered by object (generally rough) surfaces and local probes.

By rigorous calculations we shall present solutions to 2-D configurations consisting of a cylinder in front of a 2-D rough surface separating vacuum from either metal or dielectric media. Particularly important in the generation of the near fields between probe and sample are the evanescent components. We shall study them both in total internal reflection conditions and at plasmon excitation situations.

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EXPERIMENTAL STUDIES OF RESONANT LIGHT SCATTERING BY WEAKLY ROUGH METAL SURFACES

We present experimental studies of diffuse scatter arising from the excitation of surface plasmon polaritons on weakly rough metal surfaces. The surfaces are fabricated in gold-coated photoresist and are highly one-dimensional with root-mean-square vertical roughness of a few nanometers. The fabrication techniques involve both speckle-exposing methods and holographic techniques in which a Gaussian random process is written into the surface through its randomly-phased Fourier components. For the case of a surface that has only random roughness with a suitable narrow roughness spectrum, it is shown that inward and outward coupling to plasmon polaritons are allowed for a well-defined range of incident angles. Results that unambiguously demonstrate the existence of polariton-related backscattering enhancement for this type of rough surface are presented. For a gold surface whose profile is the superposition of a random roughness and a comparable sinusoidal surface component, it is shown that a dramatic rise in the p-polarized diffusely scattered intensity occurs when the periodic component permits a direct inward coupling to the plasmon polariton. For a wide range of incident angles, diffuse light bands arise that are due to the excitation of plasmon polaritons by the surface roughness, with the outward coupling provided by the periodic component.

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SHALLOW METALLIC ROUGH SURFACES : A CHALLENGE FOR RIGOROUS METHODS

Based on a classical rigorous integral formalism, a new numerical approach will be presented. The method consists in a projection of the unknown of the integral equation onto a Fourier basis, while the equation itself is sampled as in a moment method.

Since we use the beam simulation method[1] to represent the incident wave, the support of the incident field (thus that of the right-hand side of the equation) has controlled finite size. Therefore, a point matching method is more appropriate than a plane wave decomposition.

On the other hand, the behavior of the unknown is not a-priori obvious. In particular, under p-polarization, surface waves can propagate with small decay on shallow metallic surfaces. Consequently, the unknown, which is nothing but a fictitious surface current, thus closely related to the surface waves, cannot be neglected over a very long interval which can easily exceed on hundred wavelengths. For accurate computation, a moment method typically requires ten points per wavelength. It means that the size of the linear system may become much greater than one thousand. We will show that this size may be divided by a factor close to two if the unknown is described by its Fourier coefficients. This is why the method is said to be a coordinate-spectral one.

The validity of the method has been tested not only against the usual numerical tests as convergence or energy balance (for lossless media only), but also against other methods and recent experimental results by West and O'Donnell[2]. The agreement with the experimental work is very good, even though the rms height of the gold surface is small compared to the incident wavelength.

In our opinion, this method fills the gap between perturbation theories and the usual integral approach which cannot deal with long distance interactions.

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ANDERSON LOCALIZATION OF SURFACE PLASMON POLARITONS ON ROUGH METAL SURFACES THAT ARE PERIODIC ON AVERAGE

The scattering of surface plasmon polaritons by a one-dimensional surface impedance is studied on the basis of the integral equation satisfied by the scattering amplitude. By numerically solving this integral equation, we obtain the reflectivity (R) and the transmissivity (T), along with the energy radiated into the vacuum (S). The rough surface is assumed to be a sinusoidal grating, consisting of N periods of length d, upon which a random component is superimposed. The dependence of R, T and S on the surface length L = Nd is analyzed. In particular, the decay length l_T ($1/l_T = 1/l + 1/l_{rad}$, where l is the localization length and l_{rad} is the attenuation length associated with radiative losses) is obtained from the linear dependence on L of the function <log T>, where the angle brackets denote an average over the ensemble of realizations of the random surface. Thus, once l_{rad} is independently worked out, l can be calculated from the value of l_T. In this way, the frequency dependence of l is studied for frequencies in the vicinity of the edges of the surface plasmon polariton bands of the underlying periodic structure. In the gap, l is found to be smaller than it is in the allowed bands.

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A UNIFIED APPROACH TO THE VOLUME AND SURFACE SCATTERING BY MEANS OF THE SMOOTHING TECHNIQUE

The multiple scattering by a medium with a fluctuating dielectric constant is studied by means of a smoothing technique. We develop the first smoothing approximation for a stratified planar media accounting for a possible variation of the mean dielectric constant. It is shown that this approach is equivalent to a renormalized diagrammatic approach. The mean field is derived exactly using the matrix formalism. From this result, the diffuse field is derived using the Green's dyadic in a stratified media.

In a second step, this model is applied to the model of a dielectric random rough surface. The corrugation region is descrited by a fluctuating dielectric constant whose statistical properties are derived from the characteristics on the random rough surface. The results are compared with Monte Carlo simulations based on a standard surface integral equation.

The main feature of this model is its ability to describe both volume and surface scattering within the same formalism.

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TILT-INVARIANT THEORY OF ROUGH-SURFACE SCATTERING

We present the modified version of the Small-Slope Approximation (SSA) in the theory of the rough-surface scattering. SSA is a series expansion based on the small value of the surface slopes as a small expansion parameter. However, from the physical point of view, it is obvious that the average value of the slope by itself should not be the restricting parameter of the theory since it can be changed just by the choice of reference plane or coordinate system. This simple physical reason motivated us to develop a theory which incorporates the exact solution for the plane surface with arbitrary slope as a zero-order approximation. We labeled it as the Tilt Invariant Scattering Theory (TIST).

The presented theory is free from the requirement of the small value of the surface slopes. Instead of this our approximation is based on the small value of the large-scale surface curvature in comparison to the wavegength. In particular our approximation provides the exact solution for the slanted plane surface with the arbitrary slope already in the first-order term that coincides with the Kirchhoff approximation.

The small-perturbation asymptote requires two first terms of the TIST series.

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ROUGH SURFACE SCATTERING FROM GOOD AND PERFECT CONDUCTORS WITH SMALL ROUGHNESS : SOME COMPARISONS FOR P-POLARIZATION

Perturbation theory has been useful in treating scattering from conductors with small roughness. However, in the perfectly conducting limit, the expression obtained for the scattering cross section diverges when standard perturbation theory methods are used beyond lowest order*. This brings up the issue of when standard perturbation theory becomes inaccurate as the conductivity increases for good conductors. Renormalized perturbation theory developed by A.A. Maradudin and co-workers has been used in the cases of the perfect conductor with p-polarization (Neumann boundary condition) to obtain scattering cross section expressions free from the deficiencies of standard perturbation theory. Good agreement with exact integral equation results are obtained, including the case when perturbation theory is extented beyond lowest order. Here we also consider the corresponding problem for the good conductor and examine when renormalization leads to important differences in the perturbation results. Additional insight can be gained on the differences between scattering from good and perfect conductors by examining the field structure near the rough surface. Examples of these near-surface fields will also be shown.

* J.M. Soto-Crespo, M. Nieto-Versperinas, A.T. Friberg, JOSA A7, 1185, 1990.

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ENHANCED BACKSCATTERING FROM INHOMOGENEOUS MEDIUM WITH ROUGH BOUNDARY

The main motivation for this work was to investigate the features of behaviour of scattered fields for a generalized model of the medium with inhomogeneous profile of refractive index and rough boundary. The formulation of the problem involves a combination a classical smoothing method for solution Dyson and Bethe-Salpeter equations and applying the Witteker's functions for describing the propagation of the electromagnetic waves in inhomoneneous medium.

The second-order solution are obtained which exhibit backscattering enhancement. A number of special cases with various distributions refractive index with depth, limiting cases and generalizations are investigated. The angular behaviour and spectral dependences are examined.

The theoretical expressions and numerical calculations have been shown some interesting features concerning of the behaviour of scattering waves. It was found that the inhomogeneity may lead to the new resonance phonomena in backscattering. A sharp increasing a value of the enhanced backscattering peak and the dependence of the value this peak from parameters of the medium are observed. The contributions of various parameters of the medium and the boundary to the interference interactions of the waves are investigated to be distinguished with the aim of obtaining a new information about various mechanisms responsible for enhancement.

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APPLICATIONS OF THE R-MATRIX PROPAGATION TECHNIQUE IN ELECTROMAGNETIC SCATTERING

The **R**-MATRIX propagation technique, coupled with the multilayer modal expansion, is a very versatile technique for the computation of electromagnetic scattering form complex periodic structure, and it does not suffer from the numerical stability often associated with the **R**-MATRIX technique. A new multilayer modal expansion that makes the technique simple to implement will be discussed. The **R**-MATRIX the will be used to calculate the transmission through photonic medium and fractal multilayer, to calculate the surface polariton dispersion on a sinusoidal grating, and to search for guided wave modes in multilayer structures.

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ELECTROMAGNETIC WAVE SCATTERING FROM TWO-DIMENSIONAL ROUGH SURFACES BY MONTE CARLO SIMULATIONS

With the advent of modern computers, the Monte Carlo simulation of electromagnetic wave scattering from random rough surfaces is receiving greater interest. The standard method is the method of moments ; however, the full matrix inversion requires $O(N^3)$ operations where N is the number of surface unknowns. Thus numerical simulations have been restricted mostly to one-dimensional surfaces. We have developed a computationally efficient approach called the sparse-matrix flat-surface iterative approach (SMFSIA) and recently made improvements by using the flat surface as a canonical grid (SMFSIA/CAG). Each iteration step requires the calculation of the radiation from N source points to N field points on the rough surface, i.e., $O(N^2)$ operations. When the source and field points are far apart, the interaction similar to that of a flat surface (canonical grid). A Taylor series expansion of the non-near interactions results in O(Nlog(N)) operations per iteration. Using this technique, we have studied the 2-dimensional random rough surface problem for scalar waves and for electromagnetic waves. Comparisons are made with controlled laboratory experiments for an rms height of one wavelength and various correlations lengths. We show very good agreement for both co-polarization and cross-polarization results, particularly in view that the absolue values of the bistatic scattering coefficients are compared.

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LIGHT SCATTERING FROM A LOCALIZED OBJECT ON A ROUGH SURFACE

We investigate the problem of the typical change in far field scattered intensity from a randomly rough surface due to a small local change in the surface profile. Our study is motivated by the hope of retrieving useful information about the addition of a localized object on a growing random from light scattering measurement.

In our study, we follow the work in Refs[1,2] in considering a relatively smooth 2D metal surface which is characterized by a profile function $z = \zeta(R)$ ($R = (x,y)$) that consist of two components $\zeta(R) = \zeta_0(R) + \zeta'(R)$. Here $\zeta_0(R)$ is the standard random part with $\langle \zeta_0(R) \rangle = 0$ and

$$\langle \zeta_0(R)\zeta_0(R') \rangle = \sigma^2 \exp\left(-|R - R'|^2 / a^2\right) \tag{1}$$

with a being the correlation length. $\zeta'(R)$ represents a change of the random surface, e.g. due to the deposit of new atoms onto a growing semiconductor film, which we model by :

$$\zeta'(R) = \delta \exp\left(-|R - R_0|^2 / b^2\right) \tag{2}$$

where δ and b charactize the size of an object localized at R_0.

The purpose of the present work is to calculate the typical difference between the far field light intensity with and without the additional profile $\zeta'(R)$.

Specifically, we calculate the following ensemble average :

$$\begin{aligned} &\left\langle \left[I(k_f, k_0, \beta_f, \beta_0) - I_0(k_f, k_0, \beta_f, \beta_0) \right]^2 \right\rangle \\ &= (4k_{fz}k_{0z})^2 \left\langle \left[|G(k_f, k_0, \beta_f, \beta_0)|^2 - G_0(k_f, k_0, \beta_f, \beta_0)|^2 \right]^2 \right\rangle \end{aligned} \tag{3}$$

[1] G. Brown et al., Surf. Sci. 136, 381 (1984)
[2] G. Brown et al., Phys. Rev. B31, 4993 (1985)

where G is the surface polariton Green's function defined in Refs.[1,2] for the new surface, and G_0 is that for the old one ; β_0, β_f denote the polarizations of the incident and the measured beam respectively. Using the same perturbation methods that were used in Ref.[3] for the calculations in the case of random surface described by $\zeta_0(R)$, we, however, encounter a substantial difference when we add the new term $\zeta'(R)$. It appears that the momentum in the (x,y) plane is not conserved *on average* as it was in the completely random case. The averaged Green's function can no longer be written in the simple form $G(k',k) \geq \langle G(k) \rangle \delta(k' - k)$ when $\zeta'(R)$ is included.

We investigate the consequences of this model, using mainly analytical techniques, complimented by numerical simulations. In particular, we would like to show that typical variations in far field scattered intensity has a unique relation to the properties of the additional surface profile ζ', and therefore may be used to singal the onset of new additional material on a growing random surface.

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